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Origin of multiple stellar populations in globular clusters and their helium enrichment

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ABSTRACT
The various scenarios proposed for the origin of the multiple, helium-enriched populations in massive globular clusters are critically compared to the relevant constraining observations. Among accretion of helium-rich material by pre-existing stars, star formation out of ejecta from massive AGB stars or from fast rotating massive stars, and pollution by Population III stars, only the AGB option appears to be viable. Accretion or star formation out of outflowing disks would result in a spread of helium abundances, thus failing to produce the distinct, chemically homogeneous sub-populations such as those in the clusters ω Cen and NGC 2808. Pollution by Population III stars would fail to produce sub-populations selectively enriched in helium, but maintaining the same abundance of heavy elements. Still, it is argued that for the AGB option to work two conditions should be satisfied: i) AGB stars experiencing the hot bottom burning process (i.e., those more massive than $\sim 3\ M_\odot$) should rapidly eject their envelope upon arrival on the AGB, thus experiencing just a few third dredge-up episodes, and ii) clusters with multiple, helium enriched populations should be the remnants of much more massive systems, such as nucleated dwarf galaxies, as indeed widely assumed.

Key words: *(Galaxy:)* globular clusters: general – *(Galaxy:)* **globular clusters: individual:** ω **Cen, NGC 1851, NGC 2808, NGC 6388, NGC 6441, M54 –** stars: AGB and post-AGB

1 INTRODUCTION

The recent discovery of discrete, multiple stellar populations within several among the most massive globular clusters (GC) in the Milky Way (e.g., Bedin et al. 2004: Piotto et al. 2007) has brought new interest and excitement on GC research. Further excitement was added by the realization that some of these stellar populations are selectively enriched in helium to very high values ($Y \sim 0.38$), without such enrichment being accompanied by a corresponding increase in the heavy element abundance of the expected size, if at all (e.g. Norris 2004; Piotto et al. 2005, 2007).

Thus, two main closely interlaced questions arise: how did such multiple populations form? and, which kind of stars have selectively produced the fresh helium, without contributing much heavy elements? Therefore, understanding the origin of multiple populations in GCs will need to make major steps towards a better knowledge of a variety of processes such as GC formation, star formation, as well as of some long standing issues in stellar evolution, e.g., the asymptotic giant branch (AGB) phase or the effect of rotation in massive stars. Moreover, it is quite possible that some of the massive GCs with multiple populations are the compact remnants of nucleated dwarf galaxies (Bekki & Norris 2006), an aspect that widens even further the interest for this subject. All this together makes multiple populations in GCs an attractive, interdisciplinary subject of astrophysical investigation.

In this paper the main observational evidences are used to constrain the proposed possible scenarios for the origin of the multiple populations in GCs, and their associated chemical enrichment processes. In Section 2 the main relevant observational facts are briefly reviewed, and in Section 3 AGB stars and fast rotating massive stars are discussed as possible helium producers, along with Population III stars and the possible role of deep mixing during the red giant branch (RGB) phase of low mass stars. In Section 4 various proposed scenarios for the origin of the multiple populations are confronted with the relevant observational facts, arguing that only massive AGB stars appear to remain viable as helium producers. A general discussion and the main conclusions are presented in Section 5.

2 OBSERVATIONAL FACTS

The main observational facts concerning the evidence for multiple stellar populations in Galactic GCs are briefly presented in this section, separately for photometric and spectroscopic observations. Further collective information and references can be found in a recent review on these topics by Piotto (2008).

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2.1 Color-Magnitude Diagrams

2.1.1 ω Cen

It was recognized in the early 'seventies that stars in the GC ω Cen span a wide range of metallicities (Cannon & Stobie 1973; Freeman & Rodgers 1975) and since then it has been considered as a unique, exceptional cluster. Over the last several years there has been a surge of interest on this cluster, starting with the discovery that its *broad* RGB actually resolves into several distinct RGBs (Lee et al. 1999; Pancino et al. 2000). Then came the discovery that also its main sequence (MS) splits into two parallel sequences, with the bluer one being more metal rich by nearly a factor of two, hence indicating a higher helium abundance (Bedin et al. 2004; Norris 2004; Piotto et al. 2005). From the color-magnitude diagram (CMD) of the subgiant branch (SGB) region we now know that this cluster includes at least 4, possibly 5 distinct stellar populations (Sollima et al 2005; Lee et al. 2005; Villanova et al. 2007). The majority of the cluster stars ($\sim 57\%$) populate the *red* MS, have [Fe/H] = –1.7 and are assumed to have primordial helium abundance, $Y = 0.25$; $\sim 33\%$ belong to the *blue*, helium enriched MS with [Fe/H] = –1.4 and $Y \simeq 0.38$, which implies a huge helium enrichment ratio $\Delta Y/\Delta Z \simeq 70$ (Piotto et al. 2005). The residual $\sim 10\%$ of the stars belong to a metal rich component for which discrepant spectroscopic estimates exist, ranging from [Fe/H] = –1.1 ±0.2 (Villanova et al. 2007) to [Fe/H] = –0.6 (Pancino et al. 2002). Part of the discrepancy may be due to the small number of stars in this group that have been observed at high resolution. For these stars we have no direct hint on the helium abundance, but values as high as $Y \sim 0.40$ have been proposed (Sollima et al. 2005; Lee et al. 2005). How these three MS components map into the many SGB, RGB and horizontal branch (HB) components of this cluster remains partly conjectural. However, on the RGB there is well established evidence for sodium and aluminium being anticorrelated with oxygen and magnesium (Norris & Da Costa 1995; Smith et al. 2000), indicative that in a fraction of the stars material is present that was processed through hydrogen burning at high temperatures. Note that the $\sim 33\%$ overall fraction of the blue MS population takes into account the observed radial gradient in this fraction (Bellini et al. in preparation), the helium rich population being more centrally concentrated.

With a mass of $\sim 3 \times 10^6\ M_\odot$, ω Cen is the most massive GC in the Galaxy (Pryor & Meylan 1993). On this basis, it is worth estimating the amount of fresh helium and iron that was produced and is now incorporated in the minority populations. Given its mass ($\sim 10^6\ M_\odot$) and helium abundance, the intermediate metallicity, helium rich population includes $\sim 1.4 \times 10^5\ M_\odot$ of fresh helium (i.e., helium of stellar origin) and $\sim 25\ M_\odot$ of fresh iron, having adopted $Z_\odot^{\rm Fe} = 0.0013$. Similarly, the most metal rich sub-population includes $\sim 18\ M_\odot$ of fresh iron but we cannot presently estimate its helium enrichment, if any.

2.1.2 NGC 2808

Based on the multimodal HB morphology of this cluster, D'Antona & Caloi (2004) speculated that NGC 2808 harbours three main populations, each with a distinct helium abundance. This has been nicely confirmed by the discovery of a triple MS in this cluster (Piotto et al. 2007), with $\sim 63\%$ of the stars being assigned the primordial helium abundance ($Y = 0.25$), $\sim 15\%$ having helium enhanced to $Y \sim 0.30$, and $\sim 13\%$ being up to $Y \sim 0.37$. The residual $\sim 10\%$ of the stars are likely to be binaries. Given the narrow RGB sequence, no iron abundance differences appear to be associated with these helium differences. However, there appears to be a multimodal distribution of [O/Fe] ratios among the RGB counterparts of the three MS populations (Carretta et al. 2006), suggesting that most oxygen has been turned to nitrogen in the helium-enriched populations.Thus, this cluster represents an even more extreme case as far as the helium enrichment parameter $\Delta Y/\Delta Z$ is concerned, as there is no detectable increase of the overall metallicity in the helium enriched populations.

The mass of this cluster is $\sim 1.6 \times 10^6\ M_\odot$ (Pryor & Meylan 1993), and therefore the intermediate helium-rich, and the very helium-rich populations contain $\sim 1.4{\times}10^4\ M_\odot$ and $\sim 2.7{\times}10^4\ M_\odot$ of fresh helium, respectively, with no appreciable extra iron.

2.1.3 NGC 1851

No multiple main sequences have yet been detected in the CMD of this cluster, which clearly shows a double SGB, with the two components being nearly equally populated (~ 55 and $\sim 45\%$), and separated by ~ 0.1 mag (Milone et al. 2008). If interpreted in terms of age, this luminosity difference would imply an age difference of ~ 1 Gyr. Alternatively, it has been proposed that the double SGB may be due to one of the two populations being enhanced in CNO elements by a factor of ~ 2 relative to the other (Cassisi et al. 2008).

2.1.4 M54

The CMD of this cluster and of the superimposed core of the tidally disrupted Sagittarius dwarf is extremely complex, with evidence of multiple MS turnoffs (Siegel et al. 2007). However, there is no evidence of multiple populations within the cluster itself.

2.1.5 NGC 6388 and NGC 6441

Much observational and theoretical efforts have been dedicated to these two metal-rich bulge clusters, since the discovery that their HBs exhibit a remarkable blue extension (Rich et al. 1997). Unique among all GCs, they contain a number of RR Lyraes with an average period as long as 0.75 days, making them a third Oosterhoff type (Pritzl et al. 2000). The similarity of their blue HBs with those of ω Cen and NGC 2808 has been emphasized by Busso et al. (2007) who further explore helium enrichment as the cause of their unusual HB (as originally suggested by Sweigart & Catelan 1999). Based on CMDs that include HST ultraviolet bands (F225W and F336W), Busso et al. advocate a very high helium enhancements (up to $Y = 0.40$ in NGC 6388 and $Y = 0.35$ in NGC 6441)) for $\sim 15\%$ of the stars in each cluster. A more moderate helium enrichment ($Y = 0.30$ is suggested by Yoon et al. 2007), but their HB data do not include the very hot extension revealed by the UV observations.

Both clusters have a mass of $\sim 1.6{\times}10^6\ M_\odot$ (Pryor & Meylan 1993), implying that the fresh helium content of the two clusters is $\sim 3.8{\times}10^4\ M_\odot$ and $\sim 1.4{\times}10^4\ M_\odot$, respectively for NGC 6388 and NGC 6441. Given their low galactic latitude, these GCs are affected by fairly high reddening (hence differential reddening) which has so far prevented checking for the presence of multiple MSs and SGBs as would be expected if the interpretation of their HB morphology in terms of helium enhancement is correct. However, this situation may improve soon, and there is already an indication for a split in the SGB of NGC 6388 (Piotto 2008).

2.2 Abundance Anomalies

Departures from chemical homogeneity among stars within individual GCs are known since a long time (see e.g., the reviews by Kraft 1979, 1999 and Gratton, Sneden & Carretta 2004). Generally referred to as *abundance anomalies* such departures include a variety of elements and molecules, such as CN and CH bimodality, the Na-O, Al-O, and Al-Mg anticorrelations, all indicative of contamination by materials having been exposed to hydrogen burning at high temperatures ($T > 40 \times 10^6$ K). Some or all such anomalies are also exhibited by the massive clusters discussed in the previous section, but to some extent affect virtually all well studied GCs, irrespective of their mass.

For example, from the strength of the NH bands among RGB stars in NGC 6752 Yong et al. (2008) infer than the nitrogen abundance among the sample stars spans almost two orders of magnitude, with no obvious bimodality. Moreover, Yong et al. argue that a similar spread must exist in many other clusters, given that their whole RGB shows a spread in the NH-sensitive Strömgren's *cy* index of similar size to that of NGC 6752. Unfortunately, no similar *cy* data are presented for the clusters with multiple stellar populations discussed in the previous section. Among them, NGC 2808 exhibits the canonical Na-O anticorrelation, with three distinct peaks in oxygen abundance (Carretta et al. 2006), that are likely to be associated with the three distinct populations revealed by the main sequence photometry (Piotto et al. 2007). Among the clusters mentioned in section 2.1, NGC 6441 (Gratton et al. 2007) and NGC 6388 (Carretta et al. 2007) exhibit the Na-O anticorrelation and so does NGC 1851, which exhibits also Al-O anticorrelation and variations of the s-process elements (Yong & Grundahl 2008).

In ω Cen star-to-star variations of CNO elements exist as well, but their overall [C+N+O/Fe] abundance ratio appear to be constant within a factor ~ 2, as typical of all GCs (e.g., Pilachowski et al. 1988; Norris & Da Costa 1995; Smith et al. 2000, 2005). In particular, this holds for each of the various metallicity groups in ω Cen, which also exhibit large dispersions in the Al abundance (Johnson et al. 2008)

2.3 Summary of Observational Constraints

The main observational constraints that will be used in the following to narrow down the options on the origin of the multiple stellar populations in GCs can be summarized as follows:

- All GCs with confirmed (or highly probable) multiple stellar populations (ω Cen, NGC 2808, NGC 1851, NGC 6388, and NGC 6441) belong to the sample of the 10 most massive GCs in the Galaxy (with $M > 10^6\ M_\odot$).

- Massive GCs with $M > 10^6\ M_\odot$ exist that do not show evidence for multiple MSs and/or SGBs, nor multimodal HBs (e.g., 47 Tuc, Sirianni et al. 2005).

- Some sub-populations can only be understood in terms of high helium content, up to $Y = 0.37$ or more.

- Multiple stellar populations within each GCs are characterized by discrete values of the helium and iron abundances, i.e., there appears to be no composition spread within individual sub-populations as the width of the sequences on the CMDs is consistent with being due only to known photometric errors.

- Clusters with helium-enriched multiple populations also tend to exhibit evidence for Na and Al being anticorrelated with O and Mg, indicative of materials that have been exposed to hydrogen burning in a hot environment. However, such variations appear to be virtually universal among GCs, no matter whether they exhibit multiple main sequences or not. Helium enrichment does not appear to be associated with an increase of [C+N+O/Fe].

- A massive cluster (M54) sits at the center of the core of the Sagittarius DSph galaxy, and is embedded in its multiple stellar populations. This offers a concrete example of a massive GC being the nucleus of a dwarf galaxy.

3 HELIUM PRODUCERS

Critical for understanding the origin of the multiple populations in GCs is the identification of the kind of stars responsible for the production of the excess helium now incorporated in some of these populations. Three kinds of stars have been discussed in the literature, namely: AGB and Super-AGB stars, massive rotating stars, and Population III stars.

3.1 AGB and Super-AGB Stars

AGB stars have long been considered for being responsible for at least some of the composition anomalies of GC stars (D'Antona, Gratton & Chieffi 1983; Renzini 1983; Iben & Renzini 1984). Indeed, AGB stars present two attractive characteristics, namely: 1) they eject large amounts of mass at low velocity ($\sim 10-20$ km s^{-1}) which can then be retained within the potential well of GCs, and 2) the ejected materials can be highly processed through hydrogen burning at high temperature, hence being enriched in He and N, and presenting the Na-O and Al-O anticorrelations (e.g., Renzini & Voli 1981; D'Antona & Ventura 2007; Karakas & Lattanzio 2007). However, three difficulties with the AGB scenario have been pointed out: the helium abundance, the mass of the secondary populations relative to the primary one, and the constancy of [C+N+O/Fe] (e.g., Karakas et al. 2006; Karakas & Lattanzio 2007; Choi & Yi 2008). These difficulties are here addressed again.

Among AGB stars, especially interesting are those in the mass range $\sim 3-8\ M_\odot$, because they experience the hot bottom burning (HBB) process that even in the presence of carbon third dredge-up (3DU) prevents the formation of carbon stars (Renzini & Voli 1981), and will produce the Na-O and Al-O anticorrelations. Instead, in lower mass AGB stars the C/O ratio largely exceeds unity, and especially so at low metallicities. If stars were to form from these AGB ejecta they would be carbon stars, whereas such stars are absent in the clusters with multiple populations. Moreover, $\sim 3-8\ M_\odot$ stars experience the so-called second dredge-up (2DU) shortly before reaching the AGB (Becker & Iben 1979), leading to a sizable helium enrichment in the whole stellar envelope. Besides the 2DU, also the the 3DU and the HBB may contribute to increase the helium abundance in the envelope of massive AGB stars, see e.g., Fig. 11 in Renzini & Voli (1981). However, Renzini & Voli models assumed the validity of a universal core mass-luminosity relation for AGB stars, whereas Blöcker & Schönberner (1991) showed that this is no longer valid once the HBB process operates. Instead, in the presence of HBB the luminosity of AGB stars increases dramatically, driving stars to very high (superwind) mass loss rates and leading to an earlier termination of the AGB phase. Although this scenario is generally accepted, the precise duration of the AGB phase, hence the extent to which the 3DU and the HBB process operate in massive AGB stars, all remain highly model dependent. Thus, a reasonable *lower limit* to the amount of helium

enrichment is given by the 2DU contribution alone, which is fairly well established.

This assumption is consistent with the Blöcker & Schönberner (1991) result, which suggests a very prompt ejection of most of the envelope shortly after the onset of the HBB process. In practice, there would be time for the hot CNO processing of these elements originally present in the star, converting most of C and O into N (Renzini & Voli 1981), as well as for establishing the anticorrelations of Na and Al with O and Mg. These are indeed fairly rapid nuclear processes once the temperature at the base of the convective envelope is high enough. Moreover, the prompt ejection of the envelope drastically reduces the time spent on the thermally pulsing AGB (e.g., over the early estimates of Renzini & Voli), suppressing along with it most of the 3DU events, hence preventing an appreciable increase of the overall CNO abundance in the envelope. Thus, it is quite plausible for AGB stars with HBB to eject material in which helium is highly enriched, CNO nuclei are globally not significantly enhanced, but have approached their nuclear equilibrium partition, and anticorrelations among other nuclei have been established by proton captures at high temperatures. Thus, in this scenario there is no significant increase of C+N+O due to the 3DU.

In summary, it is assumed here that AGB stars experiencing the HBB process ($3 \lesssim M_{\rm i} \lesssim 8\ M_\odot$) 1) eject the whole envelope shortly after the onset of HBB, 2) the ejecta are enriched in helium solely by the 2DU, 3) too few 3DU events have time to take place, and no appreciable increase of the overall CNO abundance occurs in the envelope, and 4) HBB is sufficiently effective to promptly establish the Na-O and Al-O anticorrelations. Some observational evidences support these assumptions. The mass distribution of white dwarfs terminates at $\sim 1.1\ M_\odot$ (Bergeron, Saffer & Liebert 1992; Bragaglia, Renzini & Bergeron 1995; Koester et al. 2001), indicating that the core mass of AGB stars does not grow beyond this limit. This also implies that there must be very little, if any, increase of the core mass during the evolution of the most massive AGB stars, since the core mass of a $\sim 8\ M_\odot$ star just after completion of the 2DU is already $\sim 1.1\ M_\odot$ (Becker & Iben 1979). In addition, an AGB calibration based on globular clusters in the Magellanic Clouds indicates that in clusters younger than ~ 300 Myr there is negligible contribution of AGB stars to the bolometric luminosity of the clusters (Maraston 2005). This implies a very short AGB phase and a very small, if any, increase of the core mass during the AGB phase of stars more massive than $\sim 3\ M_\odot$.

Assuming that the first stellar generation formed in a short, virtually instantaneous burst, ~ 3 to $8\ M_\odot$ stars were shedding their envelope between ~ 30 and ~ 300 Myr after the burst. It is during this time interval that helium-enriched AGB ejecta may have accumulated inside the cluster potential well, and new stars may have formed out of them. The amount of fresh helium released by stars of initial mass $M_{\rm i}$ assuming only the 2DU contribution can be easily estimated from Becker & Iben (1979), see also Fig. 1 in Renzini & Voli (1981), where the mass of dredged-up helium is ~ 0 for $M_{\rm i} = 3\ M_\odot$ and increases linearly to $\sim 1\ M_\odot$ for $M_{\rm i} = 8\ M_\odot$. Note that only 3/4 of the dredged-up helium is "fresh", i.e., has been synthesized within the star itself, whereas 1/4 is primordial, given that $Y = 0.25$ in the first stellar generation. Therefore:

$$\Delta M_{\rm He} \simeq 0.15(M_{\rm i} - 3)\ \ M_\odot, \qquad (1)$$

which applies to a metal-poor population with $Z = 0.001$. Here only stars with initial mass in the interval $3 < M_{\rm i} < 8\ M_\odot$ experience the 2DU before the AGB phase, then soon activate the HBB process and expel the envelope according to the scenario sketched above. Thus, convolving the mass of fresh helium with the initial mass function (IMF) one can derive the total mass of fresh helium produced and expelled by these 3 to 8 $M_\odot$ stars per unit stellar mass in the whole population. For a Salpeter IMF (slope $x = 1.35$) for $M_{\rm i} > 0.5\ M_\odot$, and a flatter IMF for the lower mass stars with $x = 0.35$ for $M_{\rm i} < 0.5\ M_\odot$, one then derives:

$$M_{\rm He} \simeq 0.007 \times M_{\rm tot}, \qquad (2)$$

i.e., the mass of fresh helium released is $\sim 0.7\%$ of the original mass of the parent stellar population.

In a similar fashion, one can estimate the helium abundance Y in the ejecta of the 3 to 8 $M_\odot$ stars, which ranges from the primordial value $Y = 0.25$ for $M_{\rm i} = 3\ M_\odot$ to $Y \simeq 0.36$ for $M_{\rm i} = 8\ M_\odot$. Integrating over the same IMF, one gets that the average helium abundance of the ejecta from 3 to 8 $M_\odot$ stars is $<Y>= 0.31$. Higher values could be obtained by restricting the integration over a narrower mass range, e.g., 4 to 8 $M_\odot$ or 5 to 8 $M_\odot$. For the minimum mass approaching 8 $M_\odot$ then $< Y >$ tends to 0.35, but the total amount of released fresh helium would vanish.

Stars in the range $8 \lesssim M_{\rm i} \lesssim 10\ M_\odot$ ignite carbon non-explosively and may leave O-Ne white dwarfs, or proceed to electron-capture/core-collapse supernovae. The former outcome results if the envelope is lost in a (super)wind during helium-shell burning (the Super-AGB phase). Conversely, a supernova explosion ends the life of the star if mass loss during the Super-AGB phase is insufficient to prevent the core from growing in mass until it finally collapses (e.g., Nomoto 1984; Ritossa, Garcia-Berro & Iben 1996,1999; Poelarends et al. 2008). S-AGB stars have also experienced the 2DU and their envelope has been enriched in helium to $Y \simeq 0.38$, which makes them attractive helium contributors in the context of helium-rich populations in globular clusters (Pumo, D'Antona & Ventura 2008). Assuming that all 8 to 10 $M_\odot$ S-AGB stars leave O-Ne white dwarfs, one can estimate that the fresh helium mass produced by 3 to 10 $M_\odot$ stars would be $\sim 20\%$ higher than given by Eq. (2), i.e.,

$$M_{\rm He} \simeq 0.009 \times M_{\rm tot}. \qquad (3)$$

The accuracy of this theoretical estimate is difficult to assess. The helium mass could actually be somewhat higher if the duration of the AGB phase is long enough to allow the 3DU and HBB processes to increase the envelope helium beyond the value reached after the 2DU, but it could be lower if the mass range of the useful S-AGB stars is narrower than adopted here. (Note that in both cases the main uncertainty comes from what one is willing to assume for the mass loss during the AGB/S-AGB phases.) Still, one can regard this estimate as quite reasonable, given our current understanding of AGB/S-AGB evolution.

As far as the average helium abundance is concerned, from the inclusion of S-AGB stars one predicts a modest increase from $< Y >= 0.31$ to $< Y >\simeq 0.33$, or a little higher if considering a minimum contributing mass somewhat in excess of 3 $M_\odot$. In any event, $< Y >= 0.38$ can be regarded as the upper limit given the assumed AGB/S-AGB evolution.

Finally, it is worth noting that stars below $\sim 3\ M_\odot$ do not experience the 2DU and the HBB processes, spend a long time on the AGB in its thermally-pulsing phase, and experience repeated 3DU episodes which increase both helium and carbon in their envelopes. The fact that helium is accompanied by carbon enhancement makes these lower mass AGB stars less attractive helium producers, because the helium rich populations in GCs do not appear to be enriched in carbon (Piotto et al. 2005). Thus, the interesting mass range is ~ 3 to $\sim 10\ M_\odot$.

In summary, it is assumed that metal poor ($Z \sim 0.001$) AGB stars more massive than $\sim 3\ M_\odot$ and S-AGB stars experience the 2DU and the HBB process, and leave enough for the HBB process to convert most of the original carbon and oxygen into nitrogen, but not enough to experience a sufficient number of 3DU episodes to significantly increase the overall CNO abundance in the envelope. In this respect, the schematic AGB evolution adopted here differs from AGB models existing in the literature (e.g., Renzini & Voli 1981; Groenewegen & de Jong 1993; Herwig 2004; Izzard et al. 2004; Ventura & D'Antona 2005, 2008; Marigo & Girardi 2007).

3.2 Massive Rotating stars

Massive stars also produce sizable amounts of fresh helium, especially during their Wolf-Rayet phase. However, they also produce metals in large quantity, whereas the helium rich populations in GCs are very modestly enriched in metals (ω Cen), or not at all (NGC 2808). In the attempt to overcome this difficulty, Maeder & Meynet (2006) have proposed fast-rotating massive stars as potential helium producers in young GCs, a scenario further developed by Decressin et al. (2007), Decressin, Charbonnel & Meynet (2007) and Meynet, Decressin & Charbonnel (2008). Massive rotating stars would harbor meridional circulations bringing to the surface products of hydrogen burning (i.e., helium), while losing (helium enriched) mass in three distinct and physically separated modes: 1) a slow outflowing equatorial disk whose helium abundance increases as evolution proceeds, 2) a regular, fast, radiatively driven wind also enriched in helium in the directions unimpeded by the disk, and 3) a final core-collapse supernova explosion. Only the slow outflowing disk is considered of interest for the production of helium-enriched stars, because both radiative winds and supernova ejecta run at thousands of km/s, and would not be retained inside the relatively shallow potential well of the proto-cluster.

While physically plausible, this scenario suffers from the difficulty of predicting with any degree of confidence the efficiency of meridional circulations to mix helium into the stellar envelope, and the rate of mass loss via the outflowing disk, none of which can be estimated from first principles. Moreover, star formation would have to be confined within the outflowing disks around individual stars, before such disks are destroyed by the fast winds and supernova ejecta from nearby cluster stars, and mixed with them (Meynet et al. 2008).

3.3 RGB Self-Enrichment

In an early attempt to account for some GC abundance anomalies, Sweigart & Mengel (1979) proposed that in low mass upper RGB stars ($M \lesssim 2\ M_\odot$) mixing could extend below the formal boundary of the convective envelope, and reach well into the hydrogen burning shell. Thus, materials processed by hydrogen-burning reactions within the shell could be brought to the surface, changing the C:N:O proportions, and possibly establishing some of the abundance (anti)correlations typical of GC stars. Moreover, along with processed CNO elements, some helium enrichment could also take place, hence affecting the subsequent HB evolution (Sweigart 1997; Sweigart & Catelan 1998; Moehler & Sweigart 2006).

Observations of upper RGB stars in several GCs suggests indeed that the Sweigart-Mengel process may be at work in these stars, given that the $^{12}C/^{13}C$ ratio has reached close to its nuclear equilibrium value (~ 3.5) in virtually all of them (Recio-Blanco & de Laverny 2007). However, several abundance anomalies extend to much lower luminosities and down to the main sequence (e.g. Gratton et al. 2004), which means that RGB self-enrichment cannot be the only process at work. In particular, it cannot account for the helium-enriched MS stars, unless one is willing to consider the possibility of forming the subsequent stellar generation out of the ejecta from low-mass RGB stars. There are several difficulties with this option, such as the small mass lost by stars that may experience the Sweigart-Mengel process (i.e., those in the range ~ 1 to $\sim 2\ M_\odot$), relative to AGB/S-AGB stars, or the very long (several Gyr) time required to accumulate any sizable amount mass before being suddenly turned into stars. This very long accumulation time would imply the secondary populations to be several Gyr younger than the first generation. According to Villanova et al. (2007) there is actually a hint for the helium rich population in ω Cen being a few Gyr younger, but other interpretations of the data exist that do not require such large age differences (Sollima et al. 2005; Lee et al. 2005). Moreover, a several Gyr long accumulation time looks quite unlikely, given the possible interaction of the cluster with the galactic environment (e.g. disk crossing, tidal stripping, etc.). Perhaps more fundamentally, metal poor $\sim 1-2\ M_\odot$ stars become carbon stars on the AGB, the phase during which most of their mass loss takes place, and therefore they are not suited to provide raw material with the proper chemical composition for the production of secondary populations. For all these reasons RGB stars are considered less likely helium producer candidates. Still, RGB self enrichment may add further variance on top of other processes.

3.4 Population III Stars

Finally, in order to achieve very high $\Delta Y/\Delta Z$ values stochastic contamination by helium produced by Population III stars was suggested by Choi & Yi (2007) in a scenario in which Population III and Population II star formation temporally overlap. Here helium would be produced by very massive Pop. III stars, and metals by massive Pop. II stars, and mixing their products in various proportions one could achieve high values of $\Delta Y/\Delta Z$. Although this process may take place in nature, it does not appear to work for explaining the properties of multiple stellar populations in globular clusters. For example, in the case of NGC 2808 we have three distinct values of the helium abundance, with the same metallicity, a pattern that cannot be reproduced by mixing gas that formed the dominant cluster population with helium-rich gas from Pop. III stars. Enrichment in helium would indeed be accompanied by dilution of metals, and the helium rich population would be metal poor, contrary to the case of both ω Cen and NGC 2808.

A variant of this scenario was proposed by Chuzhoy (2006), with Population III stars being pre-enriched in helium thanks to gravitational settlement of this element within dark matter halos in the early universe. While this mechanism may produce even higher helium abundances in the ejecta of massive Population III stars, it is prone to the same difficulties of the Choi & Yi scenario if intended to account for the helium rich populations in GCs.

4 SCENARIOS FOR THE ORIGIN OF THE MULTIPLE POPULATIONS

A most stringent constraint on scenarios for the origin of multiple populations is their very nature, i.e., being indeed, multiple, discrete populations each characterized by a specific helium abundance, as most clearly evident in the case of ω Cen and NGC 2808.

This immediately implies that helium enrichment of the interstellar medium (ISM) and star formation for the second (and third) stellar generation were not concomitant processes, but instead took place sequentially. Helium-rich material was accumulated in the ISM (and mixed therein) for a sufficiently long time until suddenly a burst turned a major fraction of the ISM into stars. In fact, a continuous star formation process proceeding along with the ISM helium enrichment would have resulted in a continuous distribution of helium abundances in the newly formed stars, hence in a broadening of the main sequence rather than in well separated sequences as actually observed. In this Section one tests various proposed scenarios against this important constraint.

4.1 Accretion on Pre-existing Stars

Any gas matter lost by the first stellar generation (e.g., by its AGB stars) was necessarily less massive than the parent cluster, and hence had a lower mass density compared to the stellar component if spatially distributed in roughly the same way. A simple calculation shows that under such circumstances any stellar mass size portion of the ISM already included several lower main sequence stars. At first sight accretion onto these pre-existing seeds would seem more likely than starting new stars from scratch. Hence, already a long time ago it was favored as a likely mean to produce chemical anomalies in GCs (e.g., D'Antona, Gratton & Chieffi 1983; Renzini 1983; Iben & Renzini 1984), and has been considered even recently in the context of the helium rich populations (Tsujimoto, Shigeyama & Suda 2007; Newsham & Terndrup 2007). However, accretion depends on mass, velocity and orbit of each star inside the cluster, which would have resulted in a broad range of accreted masses from the ISM whose helium abundance was secularly evolving. After Rayleigh-Taylor mixing of accreted matter with the underlying layers of lower molecular weight, stars would now show a range of helium abundances. Thus, accretion would inevitably result in a broad, continuous distribution of stellar helium abundances, contrary to the required multiple discrete values. In spite of its attractiveness, accretion must therefore be rejected as the primary process having produced the helium-enriched populations, at least in the two clusters with clearly defined multiple main sequences.

4.2 Multiple Star Formation Episodes

This leaves multiple star formation episodes as the only mechanism able to produce successive stellar generations, each with a uniform helium (and metal) abundance. This means that helium-enriched gas had to accumulate in the potential well of the cluster, without experiencing any star formation, until something suddenly triggered the burst of star formation. Yet, it is unlikely that the efficiency of converting ISM gas into stars was near unity, and the lower this efficiency, the more massive had to be the first stellar generation in order to account for the mass of the second generation and its helium content. Any gas not converted into stars was soon lost from the proto-cluster, blown in a wind powered by high velocity stellar winds from massive stars and supernova explosions.

4.2.1 *From AGB/S-AGB Ejecta*

It is reasonable to assume that the first cluster stellar generation arose from a burst of star formation, of duration shorter than the lifetime of the most massive stars (i.e., $\lesssim$1 Myr). Then the subsequent 20–30 Myr were dominated by massive stars, whose winds and supernovae cleared the protocluster of any residual gas. After the last core-collapse supernova, i.e., 20–30 Myr since the beginning, conditions were finally established favoring the low-velocity winds from S-AGB/AGB stars to accumulate. At the beginning of the accumulation the helium abundance of such material was that pertaining to the ejected envelopes of $\sim 8-10\ M_\odot$ stars, or $Y \simeq 0.38$ according to the estimate presented in Section 3.1. Later, as AGB stars of lower and lower mass were ejecting their envelope, contributing material less enriched in helium, the helium abundance in the ISM kept steadily decreasing, down to $Y \simeq 0.31$ some 300 Myr after start. Subsequently, as the AGB started to be populated by $\lesssim 3\ M_\odot$ stars, addition of fresh helium from 3DU replaced that from 2DU, but along with it also carbon and s-process elements began to accumulate.

Clearly, the time interval between 20–30 Myr and < 300 Myr is the most propitious epoch for producing subsequent stellar generations with an helium abundance and overall composition close to that demanded by the observations. More demanding is, however, the requirement of producing a second or a third generation of the observed mass. For example, in the case of ω Cen, according to Eq. (3) its present first generation of $\sim\ 2\times10^6\ M_\odot$ produced only $\sim\ 1.6\times10^4\ M_\odot$ of fresh helium, even allowing for a full S-AGB contribution, a factor of $\sim$ 10 less than the observational requirement estimated in Section 2.1.1. We encounter here the main difficulty of the AGB scenario, as already pointed out by several authors (e.g., Karakas et al. 2006; Bekki & Norris 2006; Karakas & Lattanzio 2007), i.e., requiring a first generation of stars much more massive than that still harbored by the cluster. This difficulty is further exacerbated if the actual efficiency of star formation is less than unity.

However, the helium abundance in AGB/S-AGB stars $0.31\lesssim Y\lesssim 0.38$ is not in sharp contrast with the observational requirements from the two cases with well established multiple main sequences (ω Cen and NGC 2808), where in both cases $Y \leqslant 0.38$. Thus, AGB/S-AGB stars remain viable candidates, though we need much more of them than the AGB/S-AGB share of the first generation we now see in these clusters.

One may think that one way of having more AGB/S-AGB stars is by making recourse to a flat IMF. However, this may work only if the IMF of the subsequent generations is different from that of the first one, and in particular much steeper than it: a very contrived scenario. Otherwise, if the IMFs are the same, with a flat IMF one gets more helium from the first generation, but by as much increases the amount of fresh helium demanded by the second generation, and the discrepancy by a factor of $\sim$ 10 remains. Thus, a flat IMF does not solve the problem.

4.2.2 *From Massive Rotating Stars*

It is very difficult to prove or disprove those models of fast rotating massive stars (FRMS) in which helium is mixed in the stellar envelopes by meridional circulations, and slowly lost in an outflowing disk. Thus, I take the FRMS scenario as described in Decressin et al. (2007) at face value. One problem with this scenario is that it assumes that such disks survive long enough to produce new stars, in spite of their impervious environment in which they are bombarded from all directions by fast stellar winds and supernova explosions. But even admitting that disks manage to deliver new stars, such stars will reflect the helium abundance of the disks they are born from, which varies from one massive star to another, and for any

given stars varies as a function of its evolutionary stage. Thus, stars born out of such disks will inevitably show a spread in helium abundances, and one would have broad GC main sequences rather than multiple ones as demanded by the observations. The existence of multiple, discrete stellar populations in ω Cen and NGC 2808 rules out this FRMS scenario as a viable one to explain the helium rich populations.

Nevertheless, it is possible that meridional circulations are at work in massive stars, and bring fresh helium to the surface. If so, some meridional mixing and helium enhancement may not be confined to the very massive stars exploding as supernovae. Some helium enrichment might also take place during the main sequence phase of stars less massive than $\sim$ 8 – 10 $M_{\odot}$, which will later deliver such helium during their AGB/S-AGB phase. Therefore, if meridional mixing of helium exists in $\lesssim$10 $M_{\odot}$ main sequence stars, it would alleviate the difficulty for the AGB/S-AGB scenario outlined in the previous subsection, in particular concerning the helium abundance, yet by an amount that is hard to guess theoretically. Spectroscopic observations of $\lesssim$10 $M_{\odot}$ stars appear to be the only way to assess whether helium enrichment does indeed take place, either directly from helium line strengths in hot stars, or indirectly from C:N:O ratios indicative of deep mixing.

4.3 Metal enrichment in ω Cen

Contrary to the case of NGC 2808, in ω Cen the helium-enriched population identified by the blue main sequence is also enriched in iron, and contains some 25 $M_{\odot}$ of fresh iron that was not initially present in the first stellar population (cf. Section 2.1.1). If coming from relatively prompt Type Ia supernova events, each contributing $\sim$ 0.7 $M_{\odot}$ of iron (e.g., Iwamoto et al. 1999), at least $\sim$ 35 Type Ia supernovae (SNIa) from the first stellar generation had to explode within the helium enriched ISM, and do so within the first $\sim 10^8$ yrs. This looks quite plausible given the wide variety of distributions of SNIa delay times that theoretical models can generate (e.g. Greggio 2005). However, if the excess iron were produced by SNIa's, then the secondary population would have lower α-element to iron ratios, being selectively enriched only in iron. This is at variance with the observed [Ca/Fe], [Mg/Fe] and [Si/Fe] ratios in ω Cen RGB stars, which show no dependence on the iron abundance (Norris & da Costa 1995; Smith et al. 2000; Pancino et al. 2002). Thus, this excludes SNIa's for being responsible for the iron enrichment, and favours core collapse supernovae (CCSN), which along with iron produce also α elements. On average, each CCSN produces $\sim 0.07\,M_{\odot}$ of iron (Hamuy 2003), roughly 10 times less than each SNIa. Thus, a few hundred CCSNe are needed to produce the 25 $M_{\odot}$ of iron in the helium-rich population of ω Cen.

With the adopted IMF, one CCSN is produced every $\sim 100\,M_{\odot}$ of gas turned into stars, and therefore with its $\sim 2\times10^6\,M_{\odot}$ the first stellar generation in ω Cen has produced $\sim 20,000$ CCSNe. If the progenitor was at least 10 times more massive than the present cluster (see below), then over 2×10^5 CCSNe had been produced. Thus, it is sufficient that $\sim$ 0.1% of their ejecta were trapped inside the protocluster while mass lost by S-AGB/AGB stars had already started to accumulate. A very small time overlap between CCSN events and the appearance of S-AGB/AGB stars is necessary for this to happen, consistent with the short timescale ($\lesssim$1 Myr) postulated for the formation of the first stellar generation (cf. Section 4.2.1).

Note that these supernova explosions should have avoided to trigger any major star formation, otherwise a continuous distribution of helium and iron abundances would have resulted. What triggered the major star formation burst leading to the second generation remains unidentified. No attempt is made here to speculate on the full star formation history in ω Cen, which is much more complex given the identification of its 5 sub-populations (Sollima et al. 2005; Lee et al. 2005; Villanova et al. 2007).

5 DISCUSSION AND CONCLUSIONS

In the previous sections it has been argued that only the AGB/S-AGB scenario remains viable to account for the helium-enriched sub-populations. Still, with a serious difficulty to overcome, plus some minor ones. If our current understanding of the helium enrichment in intermediate mass stars is not grossly incorrect, then the mass of the first stellar population in a cluster such as ω Cen had to be several times larger than the present mass of the cluster. Following Bekki & Norris (2006) this difficulty can be solved if clusters such as ω Cen and NGC 2808 are the remnant nucleus of a nucleated dwarf galaxy that was torn apart by the tidal field of the Galaxy. Hence the parent first population providing the necessary raw material for the successive generation(s) would have been much more massive than these clusters are today. Some circumstantial evidence for this now widely entertained scenario is the finding that M54, one of the most massive GCs in the Galaxy, is indeed associated with the Sagittarius dwarf, albeit there is no evidence for multiple populations *within* this cluster (Siegel et al. 2007). The nucleated dwarf NGC 205 may be another example relevant to this scenario: with its tidal stream towards M31 (McConnachie et al. 2004) it may represent an early stage of the process suggested by Bekki & Norris. Its nucleus is dominated by old stellar populations, and yet it is quite bright in the WFPC2 ultraviolet F225W and F185W passbands (Cappellari et al. 1999). If the UV light comes from an extended HB (such as that of ω Cen and NGC 2808) it may also harbor helium-enriched populations, and would represent a possible testbed for the nucleated dwarf scenario of Bekki & Norris (2006).

Of course, for the nucleated dwarf scenario to work, successive stellar populations must have a much lower probability of being tidally stripped compared to the first population, otherwise the mass discrepancy would remain. This can only be achieved if the successive starbursts are far more centrally concentrated compared to the first one, i.e., the AGB/S-AGB ejecta from the first generation should collapse to the very bottom of the potential well before leading to star formation. In this connection, it is quite reassuring that the helium-enriched main sequence stars in ω Cen are indeed markedly more centrally concentrated than the others (cf. Section 2.1.1).

Besides reproducing the required helium enhancement, a successful theory for the origin of multiple stellar populations in massive GCs should also account for the observed abundance and distribution of CNO and other intermediate mass elements. Several authors (e.g., Karakas et al. 2006; Romano et al. 2007; Choi & Yi 2008) have shown that yields of existing AGB models fail to satisfy this constraint, as along with helium stellar ejecta would be enriched also in carbon from the 3DU. The question is therefore as to whether one should conclude that the fresh helium does not originate from AGB stars, or that the used theoretical yields are not correct. Given the current uncertainties affecting the massive AGB models (especially due to the treatment of mass loss and convective overshooting) it seems worth keeping a pragmatic approach, hence taking existing AGB models with special caution. The schematic AGB evolution described in Section 3.1 is quite plausible given

our ignorance of mass loss in bright AGB/S-AGB stars with HBB, and does not conflict with existing observations. Actually, it allows keeping AGB/S-AGB stars as viable helium producers for the multiple stellar generations in globular clusters.

For the present scenario to work it is essential that the AGB ejecta accumulate for a fairly long time ($\sim 10^8$ yr) without any significant star formation before suddenly a major fraction of the interstellar medium is turned into stars by a burst. This may not be such an *ad hoc* assumption, given that star formation in sporadic bursts appears to be the norm for dwarf galaxies (Gerola, Sneden & Sulman 1980), as also demonstrated by the discrete multiple generations in dwarfs such as Carina (e.g., Monelli et al. 2003).

In the case of NGC 2808 there had to be a second and a third stellar generation. If the scenario presented in this paper is basically correct, then the most helium rich secondary sub-population would have been the first to form out of the most massive AGB/S-AGB ejecta, which are the most helium rich. Then the ISM was replenished again by the ejecta of the less massive AGB stars from the first generation, plus perhaps a contribution by the secondary generation. If so, then the generation identified by the *middle* of the three main sequences in this cluster was the last to form.

Worth briefly mentioning are those observational studies that may help testing the plausibility of the AGB/S-AGB scenario proposed in this paper. Some of these tests concern the adopted AGB/S-AGB evolution and nuclear yields, in particular concerning ~ 3 to ~ 10 $M_\odot$ stars. It would be interesting to test whether the surface helium and nitrogen abundance are enhanced in ~ 6 to ~ 10 $M_\odot$ main sequence stars, possibly by the meridional circulation process advocated by Maeder & Meynet (2006), albeit high rotational velocities may hamper accurate abundance determinations, and massive stars a metal poor as stars in ω Cen and NGC 2808 are not within reach. Direct observations of bolometrically very luminous AGB/S-AGB stars in the Magellanic Clouds with very high mass loss rates should help understanding the crucial, final evolutionary stages of intermediate mass stars. Moreover, high resolution spectroscopy of very large samples (several hundreds) of stars in the various sub-populations in globular clusters should help identify unequivocal chemical signatures of the *donors* of the materials out of which these sub-populations have formed. These kind of studies are now possible thanks to the high multiplex multiobject spectrographs at 8–10m class telescopes, such as e.g., FLAMES at the VLT (Sollima et al. 2005; Carretta et al. 2006; Villanova et al. 2007). Finally, the multifrequency study of nucleated dwarfs in and around the Local Group may help testing whether the most massive globular clusters may have originated from the tidal stripping of these objects.

In conclusion, excluding scenarios that *qualitatively* conflict with observations, such as accretion, fast rotating massive stars or Population III stars, turn out to be much easier than proving others that qualitatively appear to work, but may have *quantitative* difficulties. This is the case for the AGB/S-AGB scenario advocated in this paper, where the predicted helium abundance in the secondary populations admittedly falls a little short of the highest values suggested in the literature ($Y = 0.38 - 0.40$). In this respect, one should consider than helium abundance estimates are affected by uncertainties that must be of the order of a few 0.01, hence no macroscopic discrepancy appear to exist. Still, it would help if, besides the 2DU, other processes contribute a little additional fresh helium in ~ 3 to ~ 10 $M_\odot$ stars. Additional helium may come from the HBB process operating during the AGB/S-AGB phase, and/or from meridional circulations during the main sequence phase of the progenitors of AGB/S-AGB stars.

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